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GM 9540P Cyclic Accelerated Corrosion Analysis of Nonchromate Conversion Coatings on Aluminum Alloys 2024, 2219, 5083, and 7075 Using DOD Paint Systems

by Brian E. Placzankis, Chris E. Miller, and Craig A. Matzdorf

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1. Introduction

Eight candidate Cr^{+6} free conversion coatings for study on aluminum alloys were selected based upon feedback from the U.S. Navy, U.S. Air Force (USAF), U.S. Army, and the National Aeronautics and Space Administration activities at an initial meeting with personnel representing the Environmental Security Technology Certification Program (ESTCP) and the Joint Group on Pollution Prevention (JG-PP). Overall funding for this study was provided through these organizations. The overall nonchromate study consists of two phases: phase I laboratory validation of alternatives through extensive coupon tests to evaluate paint adhesion, corrosion resistance and other criteria and phase II field testing and process validation of selected alternatives at various user facilities.

This report expands upon a previous study [1] by adding additional data on aluminum (Al) alloy 2219 and also includes *complete* data obtained throughout the General Motors (GM) 9540P [2] exposure period. As in the previous study, the focus of this particular report is constrained to a portion of phase I laboratory data, specifically GM 9540P-accelerated corrosion using exposure of aluminum alloys 2024, 2219, 5083, and 7075 specimens treated with eight candidate hexavalent chromium free pretreatments as well as one hexavalent chromium based pretreatment (Alodine 1200S) for a controlled comparison. In order to closely match conditions found in currently fielded equipment, five organic coating systems, commonly used in fielded Department of Defense (DOD) systems, were selected.

2. Experimental Procedure

Al panels (225 each nominally 7.62 × 12.7 cm) of alloys 2024-T3, 2219-T87, 5083-H131, and 7075-T6 were obtained. Prior to pretreatment and testing, all coupons were clearly labeled using a mechanical scribe to permanently affix the experimental designation. Twenty-five panels with each pretreatment combination were prepared for each alloy for GM 9540P exposure. Each set of 25 panels was further subdivided into five groups, one for each of the five selected DOD coatings. The five DOD coating systems applied were as follows:

- MIL-PRF-23377 [3] high solid epoxy primer with MIL-PRF-85285 [4] high solid polyurethane topcoat (USAF/U.S. Navy),
- MIL-PRF-85582c1 [5] waterborne epoxy with MIL-PRF-85285 topcoat (U.S. Navy),
- MIL-PRF-85582nc waterborne epoxy chromium free formulation with MIL-PRF-85285 topcoat (Experimental/JG-PP/USAF/U.S. Navy/Boeing Corp.),

- MIL- P-53030 [6] water reducible epoxy primer with MIL-C-53039 [7] chemical agent resistant single component polyurethane topcoat (U.S. Army/U.S. Marine Corps [USMC]), and
- MIL-P-53022 [8] epoxy primer with MIL-C-53039 polyurethane topcoat (U.S. Army/USMC).

The first two coating systems (23377/85285 and 85582/85285) each contained hexavalent chromium compounds in their formulations; therefore, elimination of Alodine 1200S would only reduce the total hexavalent chromium present for these cases. The remaining three coating systems were chromium free. The two U.S. Army/USMC coating systems meet chemical agent resistant coating (CARC) specifications.

Prior to painting, all of the panels were cleaned and pretreatments were applied per each of the pretreatment manufacturers' specifications at the U.S. Naval Air Systems Command (NAVAIR) facilities. The coating system's respective primer coats were applied within 24 hr subsequent to pretreatment application to each group of five panels for each pretreatment for each alloy. The topcoats were applied after 24-hr primer cure. The full coating system was then cured at ambient conditions for 14 days. The panels were then delivered from NAVAIR to the U.S. Army Research Laboratory (ARL) test facilities. Figure 1 depicts a schematic detailing the GM 9540P test matrix.

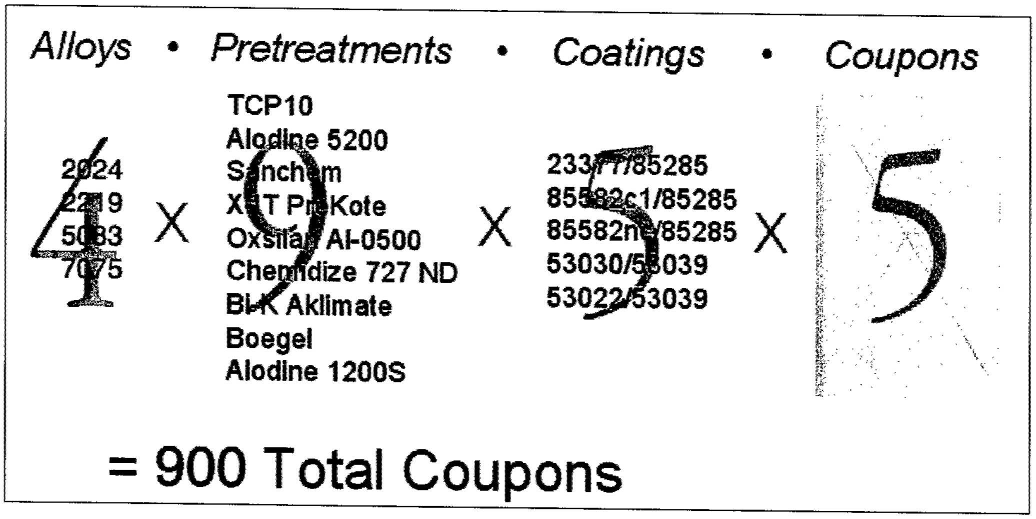


Figure 1. GM 9540P test panel matrix breakdown.

Three cyclic corrosion test chambers (CCTC) were used to evaluate the coated aluminum test panels. In order to maximize uniformity of test conditions, each alloy was given its own specific chamber. Immediately prior to exposure, the panels were all "X" scribed using a standard carbide tipped hardened steel scribe. The scribed panels were placed into the chambers (Figure 2) and tested using GM 9540P, that provides more dynamic accelerated conditions

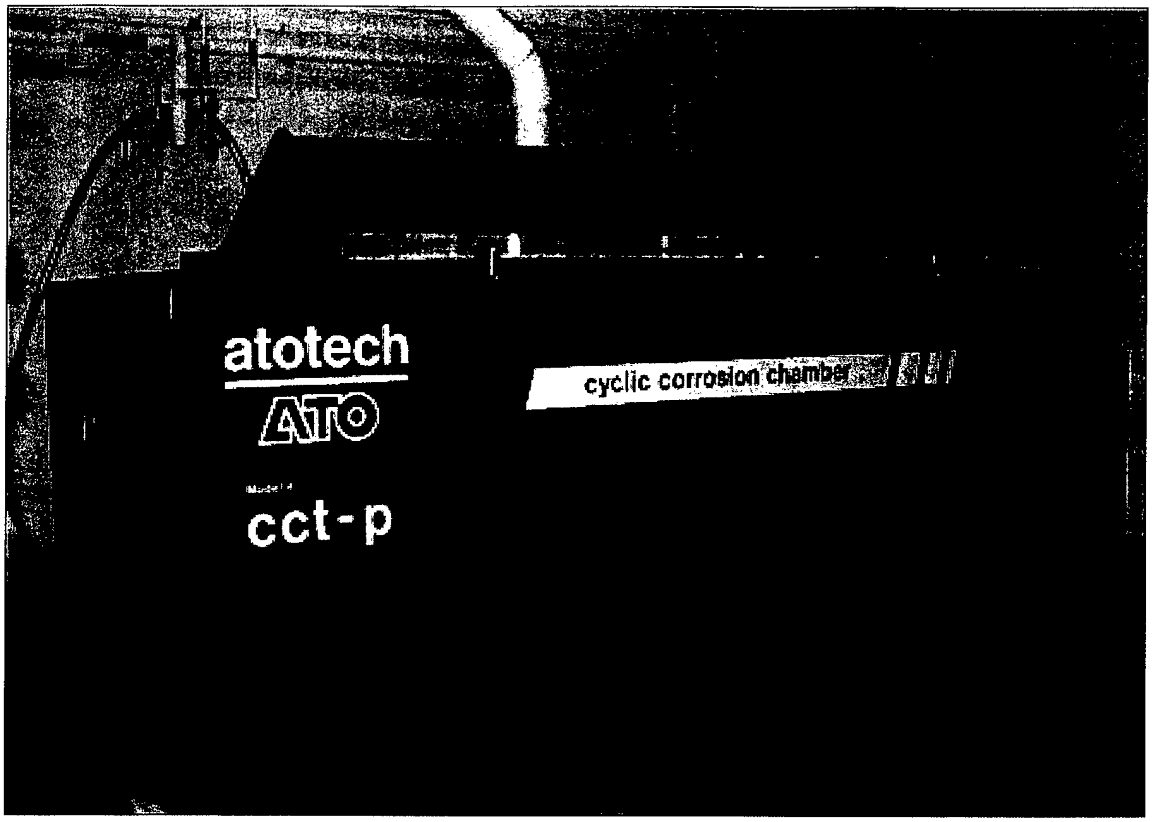


Figure 2. Test chamber configuration used for GM 9540P.

vs. conventional American Society for Testing and Materials Standard (ASTM) B 117 salt fog [9]. The GM 9540P test consists of 18 separate stages that include the following: saltwater spray, humidity, drying, ambient, and heated drying. The environmental conditions and duration of each stage for one complete GM 9540P cycle are provided in Table 1. The standard 0.9% NaCl, 0.1% $CaCl_2$, 0.25% $NaHCO_3$ test solution was used. In addition, each chamber was calibrated with standard steel mass loss calibration coupons described in GM 9540P and supplied by GM. In order to visibly chronicle the corrosion, one representative panel of each of the five test panels was chosen at 20 cycles of exposure and digitally scanned at 600-dpi resolution. Subsequent scans of the same representative panel were made at every 20 cycles until the conclusion of 120 cycles or until specimen group failure. Specimens were numerically rated for damage at each 20-cycle interval using method ASTM D 1654 [10]. Specimen group failures were defined by a rating of “0” under ASTM D 1654 for three or more of the panels in a particular alloy/pretreatment/coating set. In order to facilitate easier viewing of the inevitable large portions of data from this matrix, color codes were assigned based upon ranges of ASTM D 1654 ratings. Table 2 depicts the ASTM D 1654 rating parameters and also defines the colors and their respective rating ranges.

Table 1. GM 9540P cyclic corrosion test details.

Interval	Description	Time (min)	Temperature (±3 °C)
1	Ramp to salt mist	15	25
2	Salt mist cycle	1	25
3	Dry cycle	15	30
4	Ramp to salt mist	70	25
5	Salt mist cycle	1	25
6	Dry cycle	15	30
7	Ramp to salt mist	70	25
8	Salt mist cycle	1	25
9	Dry cycle	15	30
10	Ramp to salt mist	70	25
11	Salt mist cycle	1	25
12	Dry cycle	15	30
13	Ramp to humidity	15	49
14	Humidity cycle	480	49
15	Ramp to dry	15	60
16	Dry cycle	480	60
17	Ramp to ambient	15	25
18	Ambient cycle	480	25

Table 2. Evaluation of coated specimens subjected to corrosive environments–ASTM D 1654.

Rating of Failure at Scribe (Procedure A)		
Representative Mean Creepage From Scribe		Rating Number
(mm)	(in)	
[redacted]	[redacted]	[redacted]
Over 1.0 to 2.0	1/32 to 1/16	7
Over 2.0 to 3.0	1/16 to 1/8	6
Over 3.0 to 5.0	1/8 to 3/16	5
Over 5.0 to 7.0	3/16 to 1/4	4
[redacted]	[redacted]	[redacted]

3. Results

With the exception of premature failures under ASTM D 1654, the coated panels were all subjected to 120 cycles of GM 9540P. The creepback ratings at 20 cycle intervals are characterized in Tables 3–22. Final 120-cycle creepback ratings for all panels are listed and characterized in the Appendix. The prevalent failure mode for most of the panels was blistering along the scribe. In addition to the color coding assigned in Table 2, additional corrosion characterization is provided in the tables. Figure 3 details these additional characterizations and provides examples. In cases where blistering occurred in regions *away from the scribe*, the table cells appear with *diagonal* crosshatching. In situations where coating creepback from the scribe resulted from *adhesion loss*, *vertical* crosshatching was used. In rare situations, mixed failure mode consisting of nonscribe blistering with adhesion loss at the scribe occurred. In these situations a finer textured crosshatching pattern was used.

Table 3. ASTM D 1654 scribe creepback ratings for Al 2024 coated with 23377/85285.

Panel #	**Pretreatment**	**20 Cycles**	**40 Cycles**	**60 Cycles**	**80 Cycles**	**100 Cycles**	**120 Cycles**
2-51	Alodine 1200S	■	■	■	■	■	■
2-151	TCP10	■	■	■	■	■	■
2-251	Alodine 5200	■	■	■	■	■	■
2-351	Sanchem 7000	■	■	■	■	■	■
2-451	X-IT PreKote	■	■	■	■	7	7
2-551	Oxsilan Al-0500	■	■	■	■	■	■
2-651	Chemidize 727ND	■	■	■	■	■	■
2-751	Bi-K Aklimate	■	■	■	7	7	7
2-851A	Boegel	■	■	■	■	■	■

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 4. ASTM D 1654 scribe creepback ratings for Al 2024 coated with 85582c1/85285.

Panel #	**Pretreatment**	**20 Cycles**	**40 Cycles**	**60 Cycles**	**80 Cycles**	**100 Cycles**	**120 Cycles**
2-56	Alodine 1200S	■	■	■	■	■	■
2-156	TCP10	10	9	7	7	7	7
2-256	Alodine 5200	9	9	9	8	8	8
2-357	Sanchem 7000	5	5	5	0	0	■
2-456	X-IT PreKote	9	7	6	5	5	5
2-557	Oxsilan Al-0500	9	9	9	7	7	7
2-656	Chemidize 727ND	9	9	7	7	6	5
2-756	Bi-K Aklimate	9	9	9	9	9	9
2-856A	Boegel	■	■	■	■	■	■

Notes: Solid colors depict normal scribe creepback from corrosion.
Diagonal crosshatching denotes blistering away from immediate scribe regions.

Table 5. ASTM D 1654 scribe creepback ratings for Al 2024 coated with 85582nc/85285.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
2-61	Alodine 1200S				7	6	6
2-163	TCP10				7	6	5
2-264	Alodine 5200		7	6	6	6	6
2-361	Sanchem 7000	5	0				
2-461	X-IT PreKote		7	7	[illegible]	[illegible]	5
2-561	Oxsilan Al-0500		7	7	7	7	6
2-661	Chemidize 727ND	8	6	4	2	2	2
2-761	Bi-K Aklimate	6	4	4	4	3	3
2-862A	Boegel		[illegible]	[illegible]	4	4	4

Notes: Solid colors depict normal scribe creepback from corrosion.
Diagonal crosshatching denotes blistering away from immediate scribe regions.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 6. ASTM D 1654 scribe creepback ratings for Al 2024 coated with 53030/53039.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
2-66	Alodine 1200S				7	7	7
2-169	TCP10						
2-266	Alodine 5200		7	7	7	7	6
2-366	Sanchem 7000		7	[illegible]	[illegible]	3	3
2-470	X-IT PreKote	7	7	[illegible]	[illegible]	[illegible]	5
2-567	Oxsilan Al-0500		[illegible]	[illegible]	[illegible]	[illegible]	3
2-666	Chemidize 727ND			[illegible]	[illegible]	[illegible]	3
2-766	Bi-K Aklimate		7	[illegible]	[illegible]	[illegible]	[illegible]
2-866A	Boegel		[illegible]	[illegible]	[illegible]	[illegible]	4

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 7. ASTM D 1654 scribe creepback ratings for Al 2024 coated with 53022/53039.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
2-71	Alodine 1200S			7	7	7	6
2-172	TCP10			7	6	6	6
2-271	Alodine 5200					7	6
2-371	Sanchem 7000		6	[illegible]	[illegible]	0	0
2-471	X-IT PreKote		7	[illegible]	[illegible]	[illegible]	3
2-571	Oxsilan Al-0500				6	[illegible]	4
2-672	Chemidize 727ND			[illegible]	0	[illegible]	0
2-771	Bi-K Aklimate	9	9	9	9	9	7
2-871A	Boegel		7	7	6	6	6

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.
Diagonal crosshatching denotes blistering away from immediate scribe regions.

Table 8. ASTM D 1654 scribe creepback ratings for Al 2219 coated with 23377/85285.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
9-51	Alodine 1200S	■	■	■	■	■	■
9-153	TCP10	■	■	■	■	■	7
9-251	Alodine 5200	■	■	■	■	■	■
9-351	Sanchem 7000	■	■	6	6	6	6
9-451	X-IT PreKote	■	■	■	■	■	■
9-551	Oxsilan Al-0500	■	■	■	■	■	■
9-651	Chemidize 727ND	7	6	■	■	▨	▨
9-751	Bi-K Aklimate	■	■	■	6	▨	▨
9-853A	Boegel	■	■	6	6	▨	▨

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 9. ASTM D 1654 scribe creepback ratings for Al 2219 coated with 85582c1/85285.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
9-56	Alodine 1200S	■	■	■	■	■	■
9-156	TCP10	■	■	■	■	■	■
9-256	Alodine 5200	■	■	■	■	■	■
9-358	Sanchem 7000	■	■	6	6	6	6
9-457	X-IT PreKote	■	■	■	■	■	7
9-556	Oxsilan Al-0500	■	■	■	■	■	■
9-656	Chemidize 727ND	7	■	■	■	▨	▨
9-756	Bi-K Aklimate	■	■	■	■	7	7
9-859A	Boegel	■	■	■	■	■	■

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 10. ASTM D 1654 scribe creepback ratings for Al 2219 coated with 85582nc/85285.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
9-64	Alodine 1200S	■	7	6	■	▨	▨
9-161	TCP10	■	6	6	■	▨	▨
9-261	Alodine 5200	■	7	6	■	▨	▨
9-364	Sanchem 7000	■	■	■	■	■	■
9-461	X-IT PreKote	6	■	■	■	■	■
9-564	Oxsilan Al-0500	■	■	■	■	■	▨
9-661	Chemdize 727ND	■	■	■	■	■	■
9-764	Bi-K Aklimate	■	■	■	■	■	■
9-861A	Boegel	■	■	■	■	■	■

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 11. ASTM D 1654 scribe creepback ratings for Al 2219 coated with 53030/53039.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
9-66	Alodine 1200 S		4	3	3	2	0
9-166	TCP10	6	4	2	0	0	0
9-266	Alodine 5200	7	4	2	1	0	0
9-366	Sanchem 7000	4	2	0			
9-467	X-IT PreKote	3	1	0			
9-566	Oxsilan Al-0500	[illegible]	0	0			
9-666	Chemidize 727ND	2	0				
9-766	Bi-K Aklimate	2	0				
9-869A	Boegel	2	0				

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 12. ASTM D 1654 scribe creepback ratings for Al 2219 coated with 53022/53039.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
9-71	Alodine 1200S		5	0	0	0	0
9-171	TCP10	7	5	5	5	3	2
9-271	Alodine 5200	6	5	3	2	1	0
9-371	Sanchem 7000	3	0	0	0		
9-473	X-IT PreKote	2	0	0			
9-573	Oxsilan Al-0500	5	1	0			
9-671	Chemidize 727ND	2	0				
9-771	Bi-K Aklimate	2	0	0			
9-871A	Boegel	5	4	2	1	0	

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 13. ASTM D 1654 scribe creepback ratings for Al 5083 coated with 23377/85285.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
5-51	Alodine 1200S						
5-151	TCP10						
5-251	Alodine 5200						
5-351	Sanchem 7000						
5-451	X-IT PreKote						
5-551	Oxsilan Al-0500						
5-651	Chemidize 727ND						
5-751	Bi-K Aklimate						
5-851A	Boegel						

Note: Solid colors depict normal scribe creepback from corrosion.

Table 14. ASTM D 1654 scribe creepback ratings for Al 5083 coated with 85582c1/85285.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
5-56	Alodine 1200S						
5-156	TCP10						
5-256	Alodine 5200						
5-360	Sanchem 7000			7	7	7	7
5-456	X-IT PreKote						
5-556	Oxsilan Al-0500						
5-656	Chemidize 727ND						
5-756	Bi-K Aklimate						
5-856A	Boegel						

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.

Table 15. ASTM D 1654 scribe creepback ratings for Al 5083 coated with 85582nc/85285.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
5-61	Alodine 1200S						
5-161	TCP10						
5-261	Alodine 5200						
5-364	Sanchem 7000	7					
5-462	X-IT PreKote						
5-561	Oxsilan Al-0500						
5-661	Chemidize 727ND		7	7	7	7	7
5-761	Bi-K Aklimate						
5-861A	Boegel						

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 16. ASTM D 1654 scribe creepback ratings for Al 5083 coated with 53030/53039.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
5-66	Alodine 1200S						
5-167	TCP10						
5-266	Alodine 5200						
5-366	Sanchem 7000	8	7	7	7	7	7
5-466	X-IT PreKote						
5-566	Oxsilan Al-0500						
5-666	Chemidize 727ND						
5-766	Bi-K Aklimate						
5-866A	Boegel						

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.

Table 17. ASTM D 1654 scribe creepback ratings for Al 5083 coated with 53022/53039.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
5-71	Alodine 1200S	■	■	■	■	■	■
5-171	TCP10	■	■	■	■	■	■
5-271	Alodine 5200	■	■	■	■	■	■
5-371	Sanchem 7000	■	■	■	■	■	■
5-471	X-IT PreKote	■	■	■	■	■	■
5-571	Oxsilan Al-0500	■	■	■	■	■	■
5-671	Chemidize 727ND	■	■	■	■	■	■
5-771	Bi-K Aklimate	■	■	■	7	7	7
5-871A	Boegel	■	■	■	■	■	■

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 18. ASTM D 1654 scribe creepback ratings for Al 7075 coated with 23377/85285.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
7-51	Alodine 1200S	■	■	■	■	■	■
7-151	TCP10	■	■	■	■	■	■
7-253	Alodine 5200	6	6	6	6	6	6
7-351	Sanchem 7000	■	■	■	■	■	■
7-451	X-IT PreKote	■	■	■	■	■	■
7-551	Oxsilan Al-0500	■	■	■	■	■	■
7-651	Chemidize 727ND	■	■	■	■	■	■
7-751	Bi-K Aklimate	■	■	■	■	■	■
7-851A	Boegel	■	■	■	■	■	■

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.

Table 19. ASTM D 1654 scribe creepback ratings for Al 7075 coated with 85582c1/85285.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
7-56	Alodine 1200S	■	■	■	■	■	■
7-156	TCP10	■	■	■	■	■	■
7-259	Alodine 5200	[illegible]	■	■	■	■	■
7-357	Sanchem 7000	■	9	[illegible]	6	■	■
7-456	X-IT PreKote	■	■	■	■	■	■
7-556	Oxsilan Al-0500	■	9	9	7	7	6
7-656	Chemidize 727ND	7	7	7	6	6	6
7-756	Bi-K Aklimate	■	9	9	9	9	9
7-856A	Boegel	■	■	■	■	■	■

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 20. ASTM D 1654 scribe creepback ratings for Al 7075 coated with 85582nc/85285.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
7-61	Alodine 1200S						
7-161	TCP10						
7-261	Alodine 5200	6					
7-361	Sanchem 7000						
7-461	X-IT PreKote		6	6			
7-561	Oxsilan Al-0500			8	7	6	6
7-661	Chemidize 727ND		7				
7-765	Bi-K Aklimate	7					
7-861A	Boegel		7	7	[illegible]	5	5

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 21. ASTM D 1654 scribe creepback ratings for Al 7075 coated with 53030/53039.

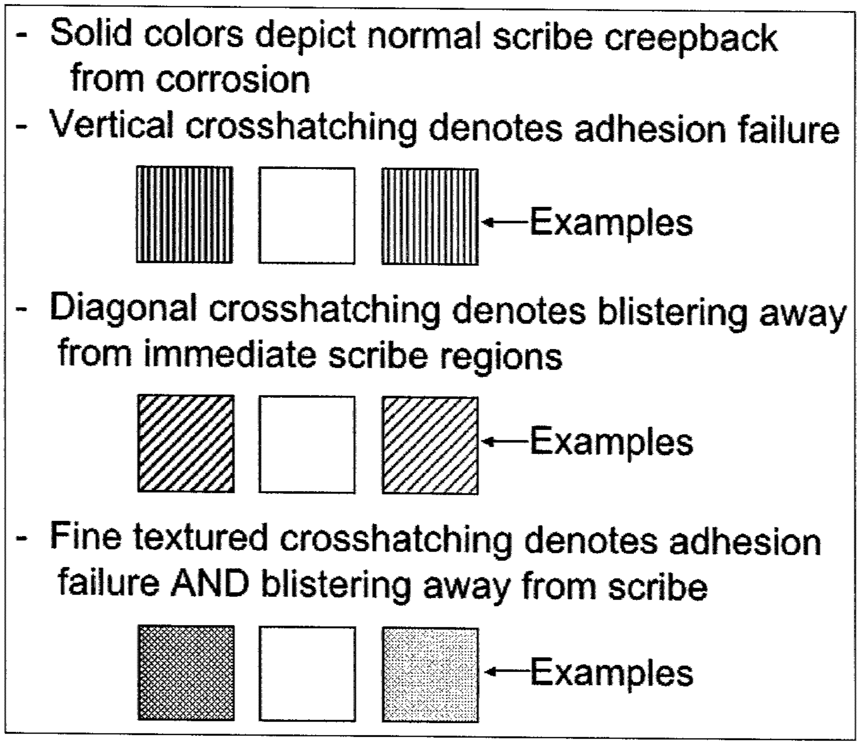
Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
7-66	Alodine 1200S					7	7
7-166	TCP10	8	8	7	7	7	7
7-268	Alodine 5200	6					
7-366	Sanchem 7000						
7-466	X-IT PreKote	7					
7-568	Oxsilan Al-0500	7					
7-669	Chemidize 727ND						
7-769	Bi-K Aklimate						
7-866A	Boegel		7	7	[illegible]	[illegible]	[illegible]

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 22. ASTM D 1654 scribe creepback ratings for Al 7075 coated with 53022/53039.

Panel #	Pretreatment	20 Cycles	40 Cycles	60 Cycles	80 Cycles	100 Cycles	120 Cycles
7-71	Alodine 1200S				7		
7-174	TCP10						
7-271	Alodine 5200			7	7	7	6
7-371	Sanchem 7000						
7-473	X-IT PreKote	6					
7-571	Oxsilan Al-0500						
7-674	Chemidize 727ND						
7-771	Bi-K Aklimate						
7-871A	Boegel						

Notes: Solid colors depict normal scribe creepback from corrosion.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.



- Solid colors depict normal scribe creepback from corrosion
- Vertical crosshatching denotes adhesion failure
- Diagonal crosshatching denotes blistering away from immediate scribe regions
- Fine textured crosshatching denotes adhesion failure AND blistering away from scribe

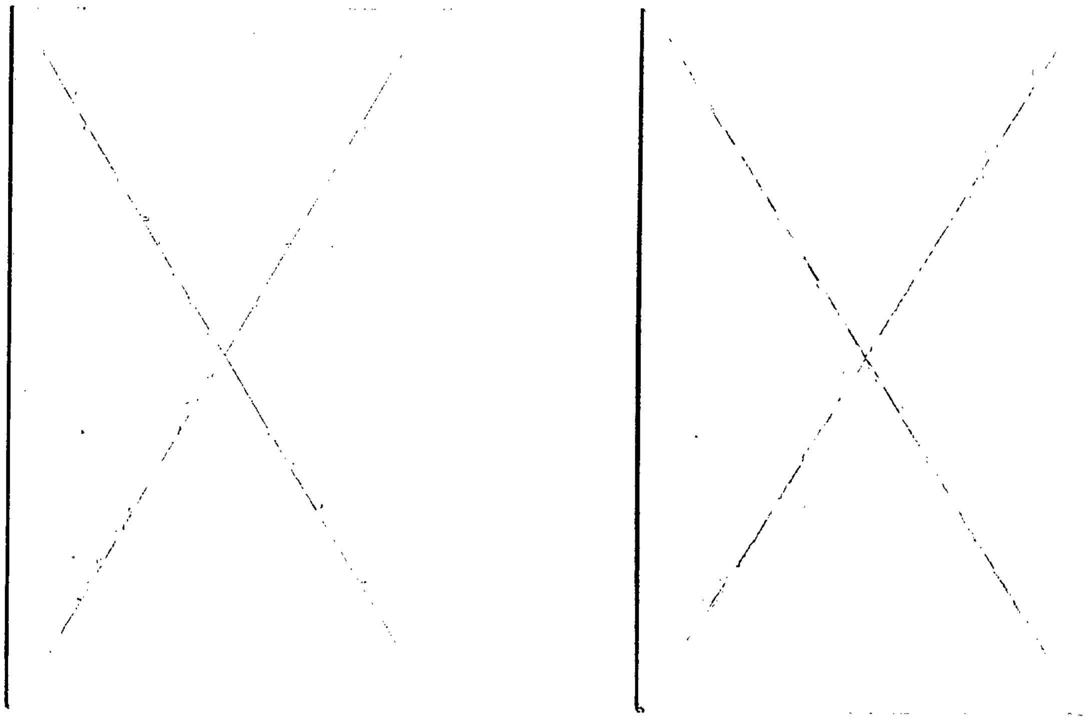
Figure 3. Color code shading patterned for detailed descriptions.

3.1 Al 2024

For Al 2024, the top-performing pretreatments were clearly defined. For this particular alloy, it was the coating system selection that aided in revealing the better performers. For the hexavalent chromium bearing 23377/85285 coating system, all of the pretreatments performed well for the most part and completed 120 cycles with the highest ratings among the coating systems (Table 3).

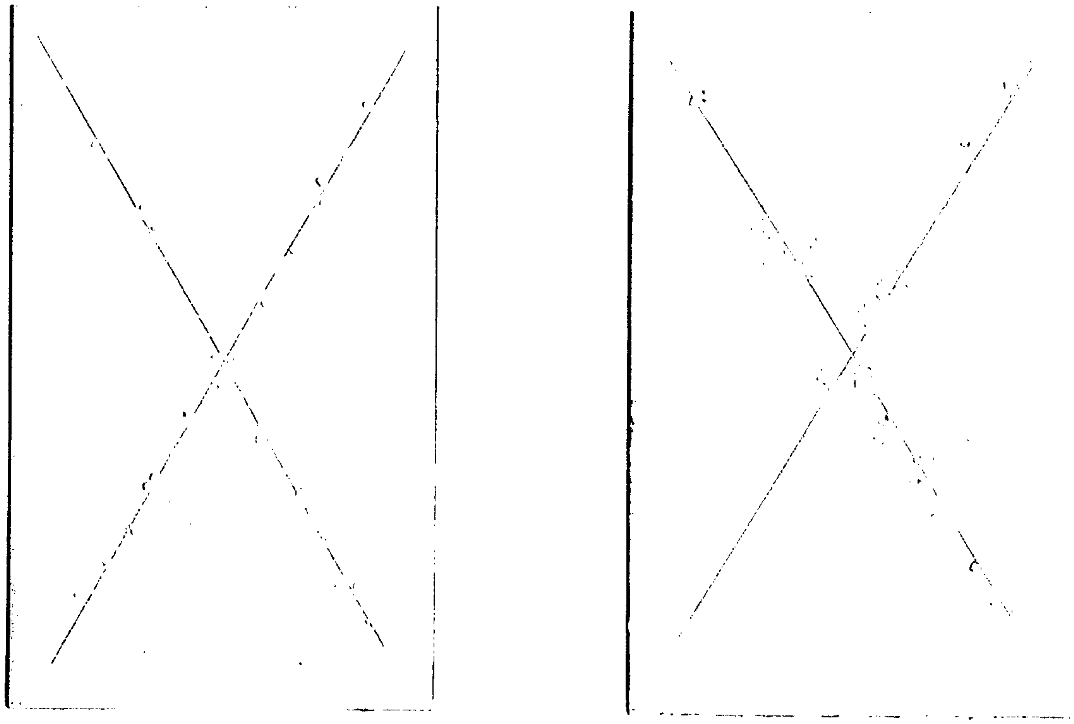
Although the 85582c1/85285 coating system also contains hexavalent chromium, overall it performed much worse when compared vs. the 23377/85285 system for the same pretreatments. In addition to scribe creepback this coating system was very susceptible to blistering away from the scribe with two exceptions. The two exceptions for this system with the best performance were Alodine 1200S and Boegel (Table 4).

For the remaining three coating systems, 85582nc/85285, 53030/53039, and 53022/53039, the best performance was provided by the NAVAIR TCP and Alodine 1200S pretreatments (Tables 5–7 and Figures 4 and 5). In the specific case of the waterborne primed 53030/53039 CARC system, the TCP pretreatment even exceeded the performance for Alodine 1200S. Alodine 5200 pretreatment rendered respectable performance at or near the leaders for these chromium-free coating systems.



(a) Alodine 1200S

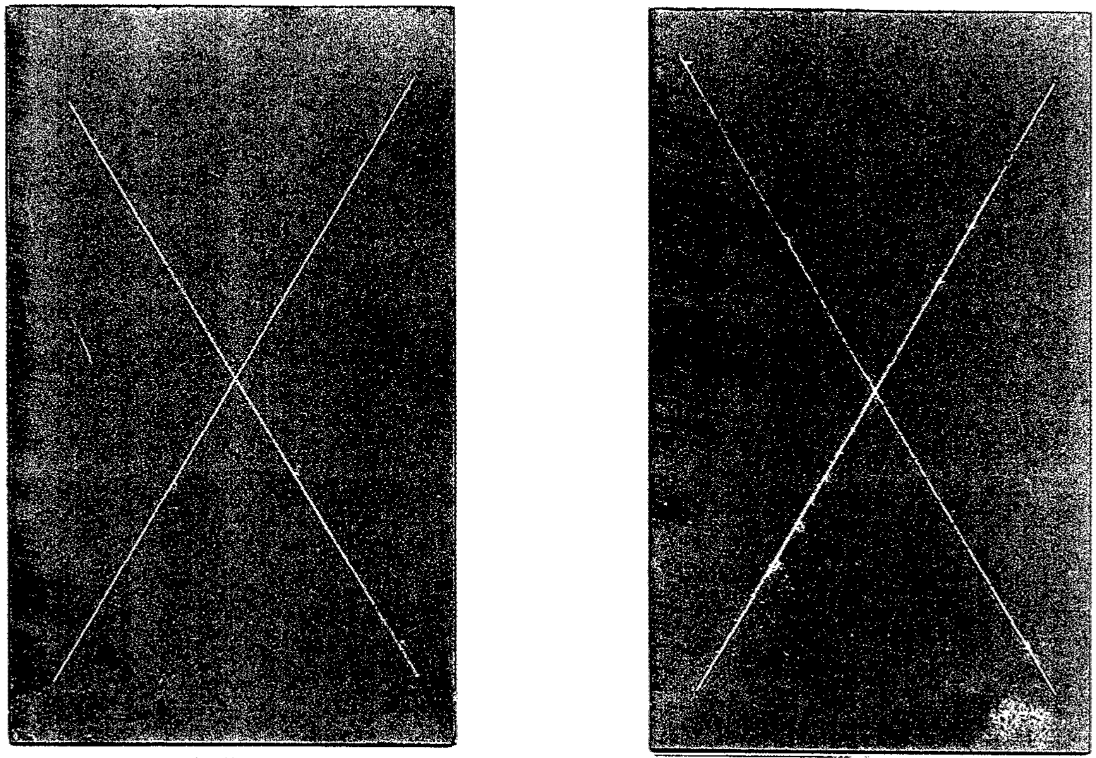
(b) TCP



(c) Alodine 5200

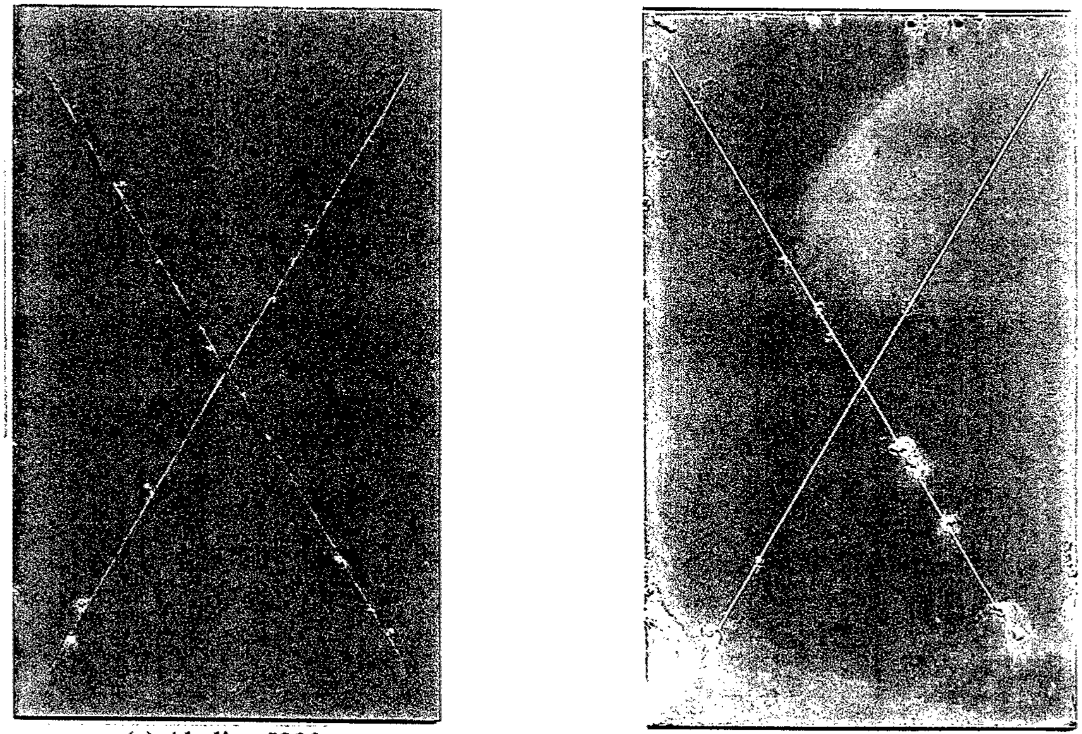
(d) Boegel

Figure 4. Al 2024 with 85582nc/85285 at 120 cycles GM 9540P.



(a) Alodine 1200S

(b) TCP



(c) Alodine 5200

(d) Boegel

Figure 5. Al 2024 with 53030/53039 at 120 cycles GM 9540P.

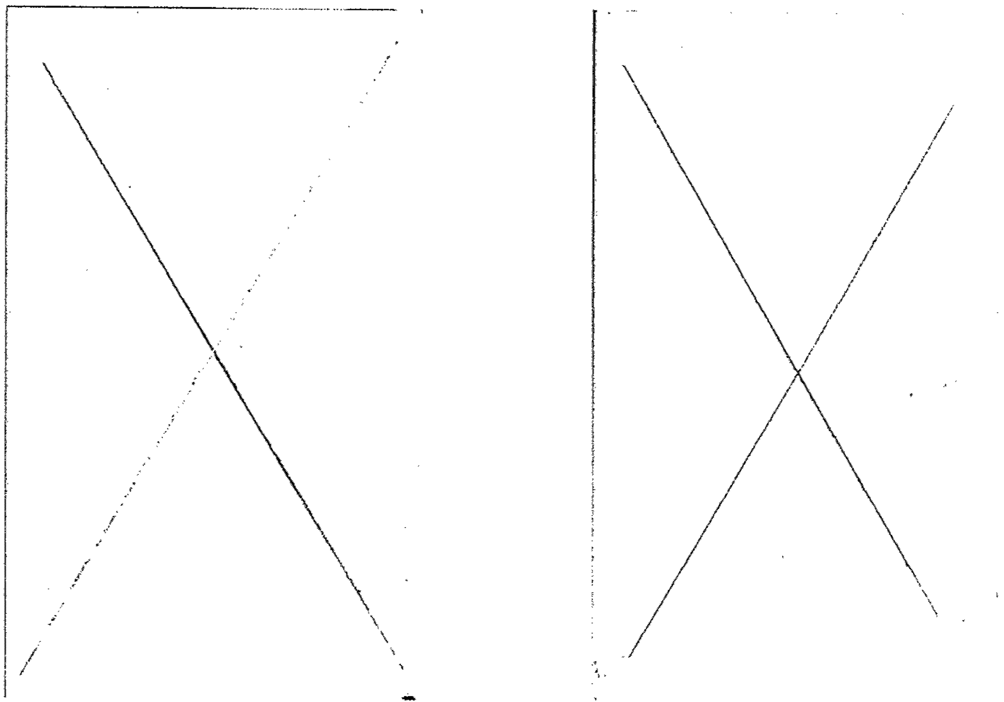
3.2 Al 2219

Of all the Al alloys examined in this study, Al 2219 with its high copper (Cu) content is by far the most corrosion prone and provides a difficult task for even hexavalent-based Alodine 1200S. For the chromate based 23377/85285 coating system, although all pretreatments lasted the full 120-cycle duration, significant corrosion damage occurred on many of the pretreatments. The best performers for this coating system were Alodines 1200S and 5200 and Oxsilan. TCP showed the remaining pretreatments (Table A-8, Appendix). For the chromate containing 85582c1/85285 system, the best performers were Alodines 1200S and 5200, NAVAIR TCP, Oxsilan, and Boegel. The remaining pretreatments performed in the intermediate range with ratings ranging from 5 to 7 (Table 9, Figures 6 and 7).

For the three chromate-free coating systems: 85582nc/85285, 53030/53039, and 53022/53039, there was significant corrosion damage and most of the pretreatments were unable to endure 120 cycles without early specimen group failure. Although the corrosion damage was severe, the most consistent performers for these systems were NAVAIR TCP, and Alodines 1200S and 5200. Oxsilan rated only marginally better than the remaining pretreatments for the chromate-free coatings but only by virtue of not completely failing as soon (Tables 10–12).

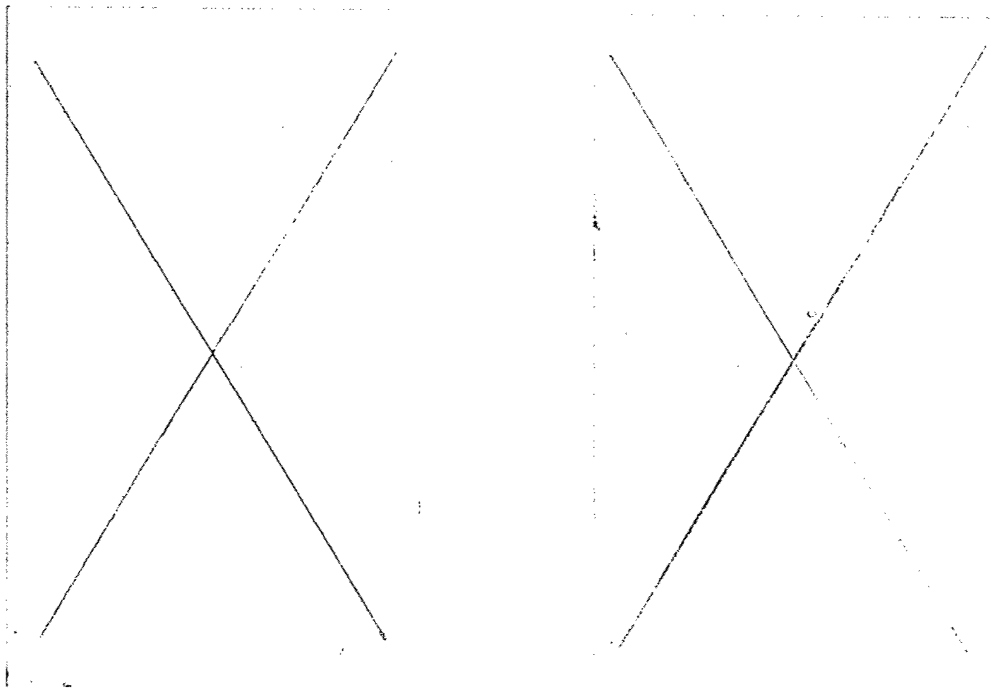
3.3 Al 5083

Al 5083, an alloy known for its stable protective oxide layer, does not usually significantly corrode, even under accelerated conditions. Due to its widespread use in tactical ground systems, accelerated corrosion methods such as GM 9540P are still necessary for this alloy for quality assurance purposes and also for detecting potential coating adhesion issues. As expected, for Al 5083, most pretreatments sustained the full 120-cycle duration without any noticeable damage across all five coating systems as seen in Tables 13–17. As in Al 2024, the 23377/85285 coating system proved superior, and there was no significant creepback resulting from corrosion or coating system delamination. For 85582c1/85285, there were adhesion issues with the Sanchem 7000 pretreatment that rated a "7" by 60 cycles and then stabilized for the balance of 120 cycles. For the nonchromium-based formulation 85582nc/85285, the problems with the Sanchem 7000 process were more pronounced with more severe creepback resulting from actual corrosion. Any damage for Al 5083 is significant because even in a bare uncoated and untreated condition, this alloy will not significantly corrode. For this same coating system, the Chemidize 727ND pretreatment also showed blistering though to a somewhat less severe degree along the scribe. For the waterborne 53030 primer-based CARC system, Sanchem 7000 exhibited damage due to adhesion failure similarly as previously noted. For the solvent primer-based 53022/53039 CARC system, the only noticeable damage occurred on the Bi-K Aklimate pretreated system.



(a) Alodine 1200S

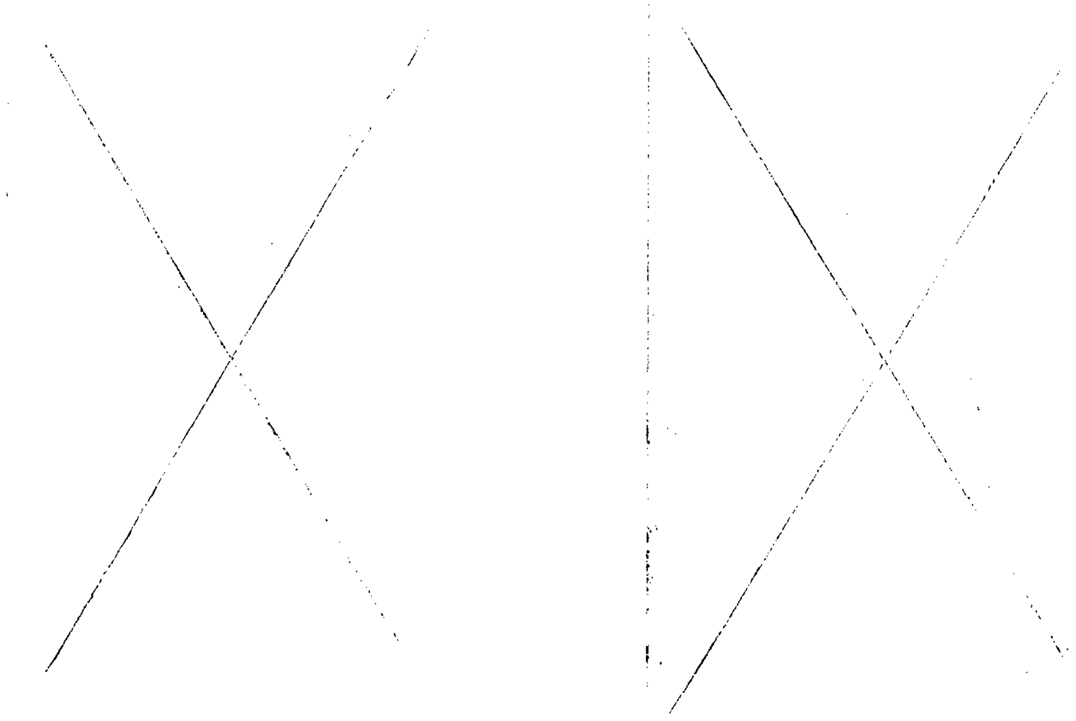
(b) TCP



(c) Alodine 5200

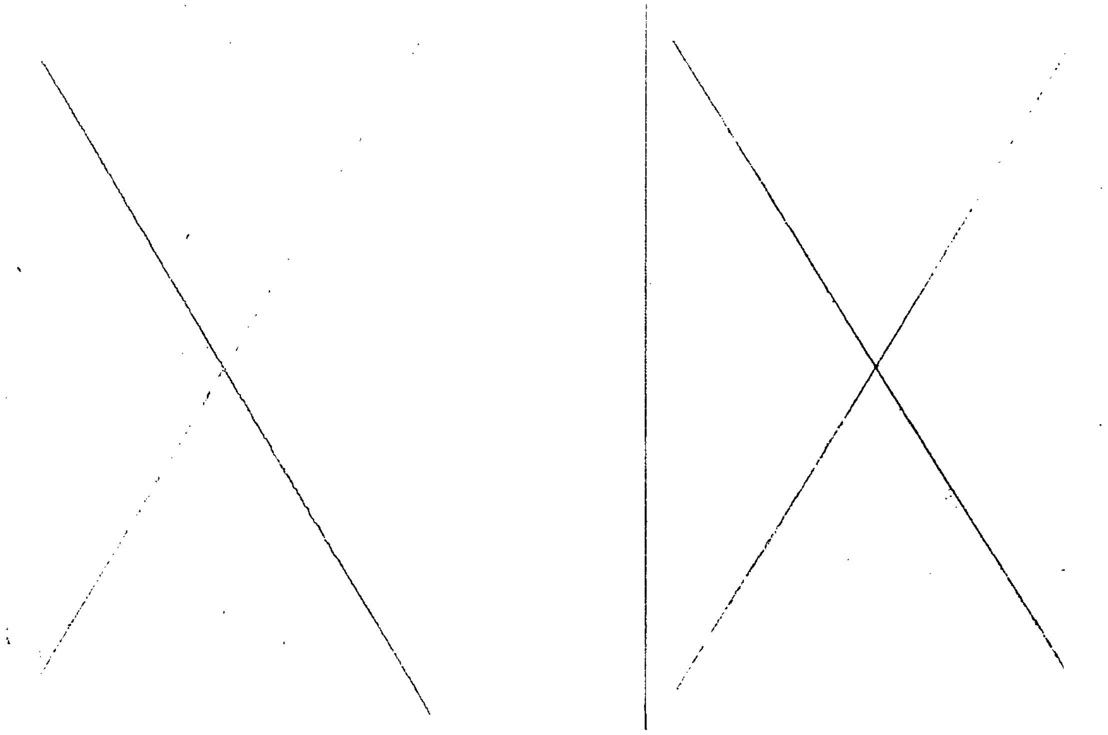
(d) Oxsilan AL-0500

Figure 6. Al 2219 with 85582c1/85285 at 120 cycles GM 9540P.



(a) X-IT PreKote

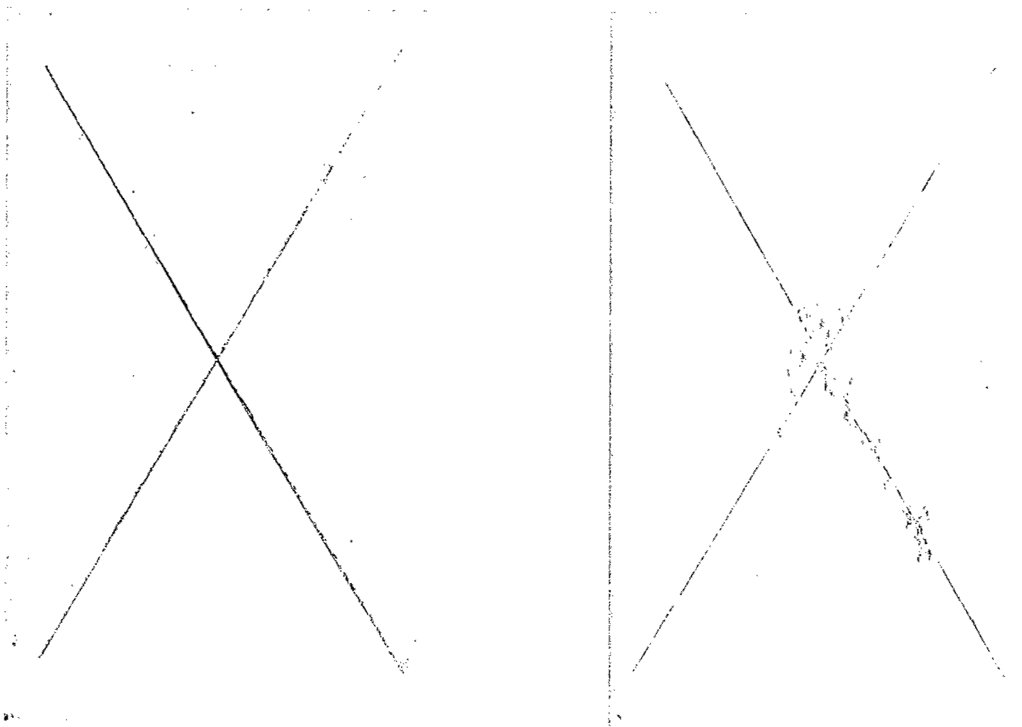
(b) Chemidize 727ND



(c) Bi-K Aklimate

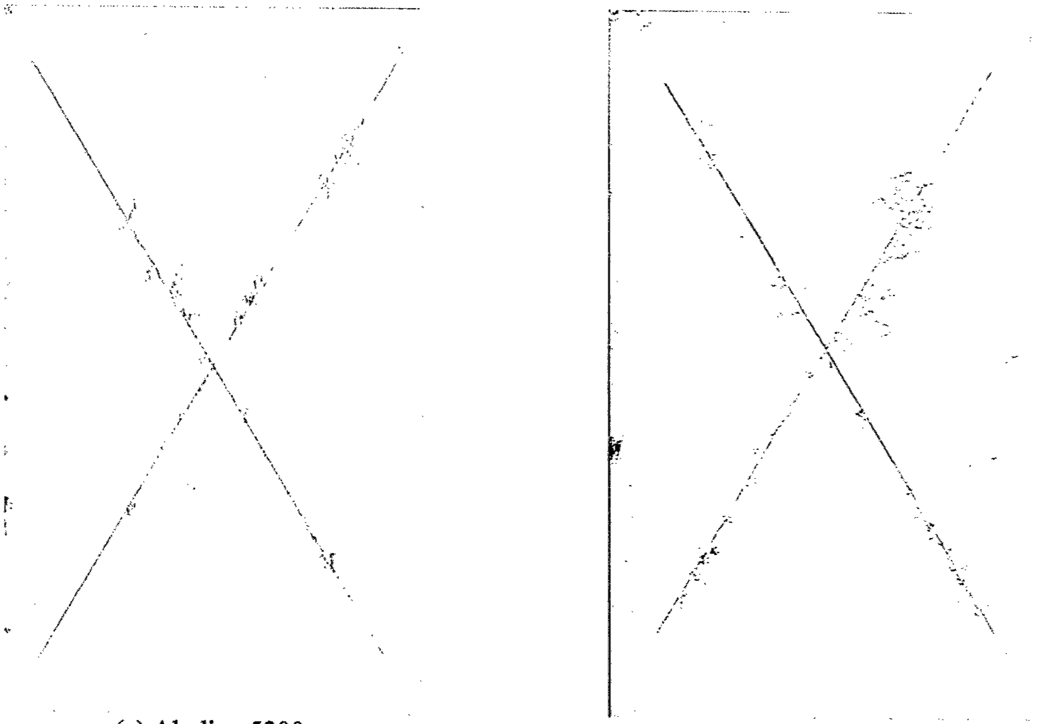
(d) Boegel

Figure 7. Al 2219 with 85582c1/85285 at 120 cycles GM 9540P.



(a) Alodine 1200S

(b) TCP



(c) Alodine 5200

(d) Oxsilan Al-0500

Figure 8. Al 2219 with 85582nc/85285 at 120 cycles GM 9540P.

3.4 Al 7075

With the exception of Al 2519, Al 7075 specimens surprisingly exhibited the most severe damage from corrosion during GM 9540P exposure. For the coating system 23377/85285, as in the other alloys, most all of the pretreatments performed well with little or no damage to the scribed region. The exception for this case was Alodine 5200 with damage characterized by coating delamination from the scribed regions (Table 18).

For the 85582c1/85285 system, the top performers with little or no damage were Alodine 1200S, TCP, X-IT PreKote, and Boegel. Other pretreatments for this system were disqualified either by lower ratings due to corrosion, delamination, or both. Sanchem 7000 pretreatment failed across the majority of its five panels by 100 cycles (Table 19).

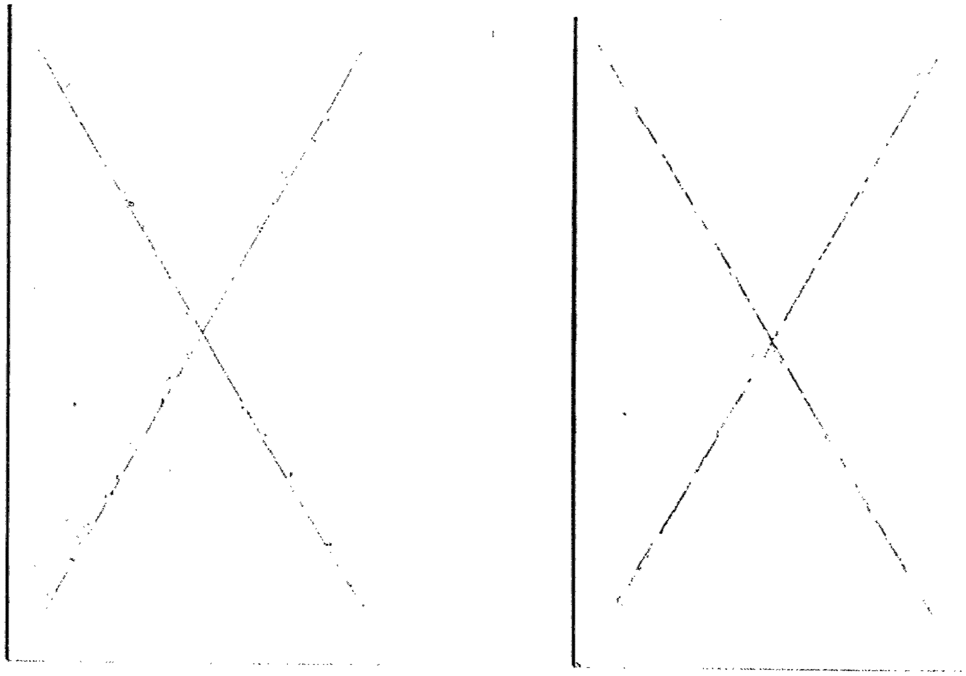
For the chromate-free 85582nc/85285 system, the only top performers were Alodine 1200S and TCP (Table 20 and Figure 9). The next best performing alternatives containing no chrome whatsoever were the distant runners up Alodine 5200 and Boegel, which both rated a "5" through 120 cycles. Panels failing the exposure for this coating system were Sanchem 7000 and Bi-K Aklimate. In particular, the failure for Sanchem 7000 was severe with partial series failures at 20 cycles and specimen group failure by 40 cycles exposure.

As in previous alloys, the CARC systems were more susceptible to corrosion attack than their aircraft coating counterparts. For the waterborne primer system 53030/53039 chronicled in Table 21, Alodine 1200S and TCP pretreatments performed best. The mode of creepback progression on the TCP-treated panel was due to delamination of the coating. The next best performers for this coating system were Alodine 5200 and Boegel; however, their performance at best was fair with both pretreatments only rating a "4" at the conclusion of 120 cycles. Series that failed prior to completion of 120 cycles in order of decreasing severity included Chemidize 727ND, Bi-K Aklimate, and Sanchem 7000.

A comparison between Tables 21 and 22 shows the 53022/53039 system performance for all pretreatments overall was better than for the waterborne primer CARC series for Al 7075. The NAVAIR TCP pretreatment was clearly superior for this group as shown in Figure 10. Next best finishers were Alodines 1200S and 5200 with ratings at 120 cycles of "5" and "6," respectively. Boegel rated a "3" with the others all rating a "2" or lower at 120 cycles. The only failure prior to 120 cycles was the Chemidize 727ND pretreatment, which failed as a set by 60 cycles.

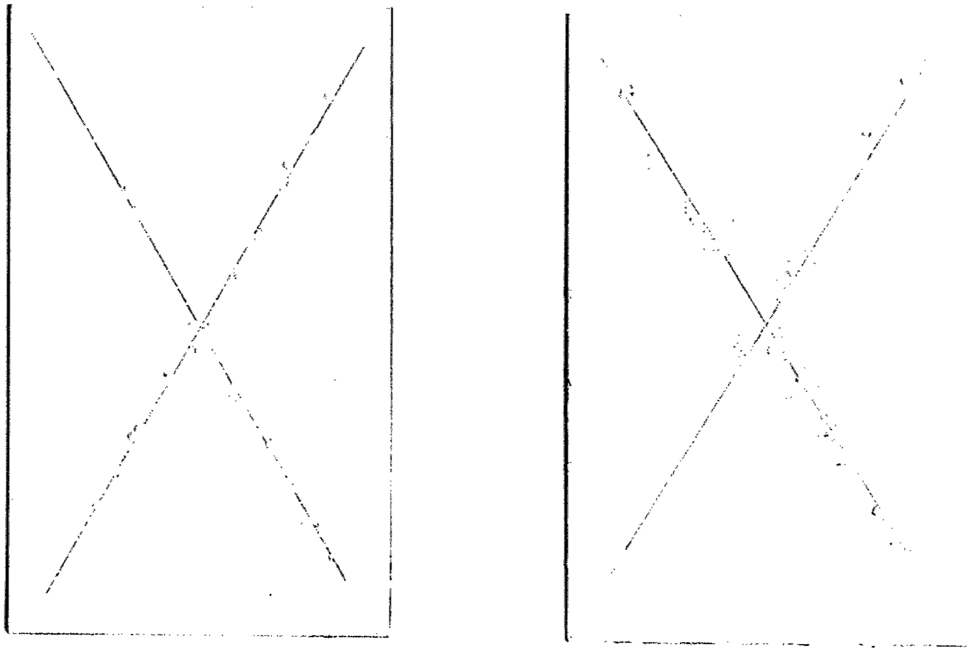
4. Discussion

The purpose of this study was to provide GM 9540P-accelerated cyclic corrosion performance data for alternatives to Cr^{+6} based Alodine 1200S. It should be stressed that good performance in accelerated corrosion testing alone does not guarantee a good conversion coating. Other factors



(a) Alodine 1200S

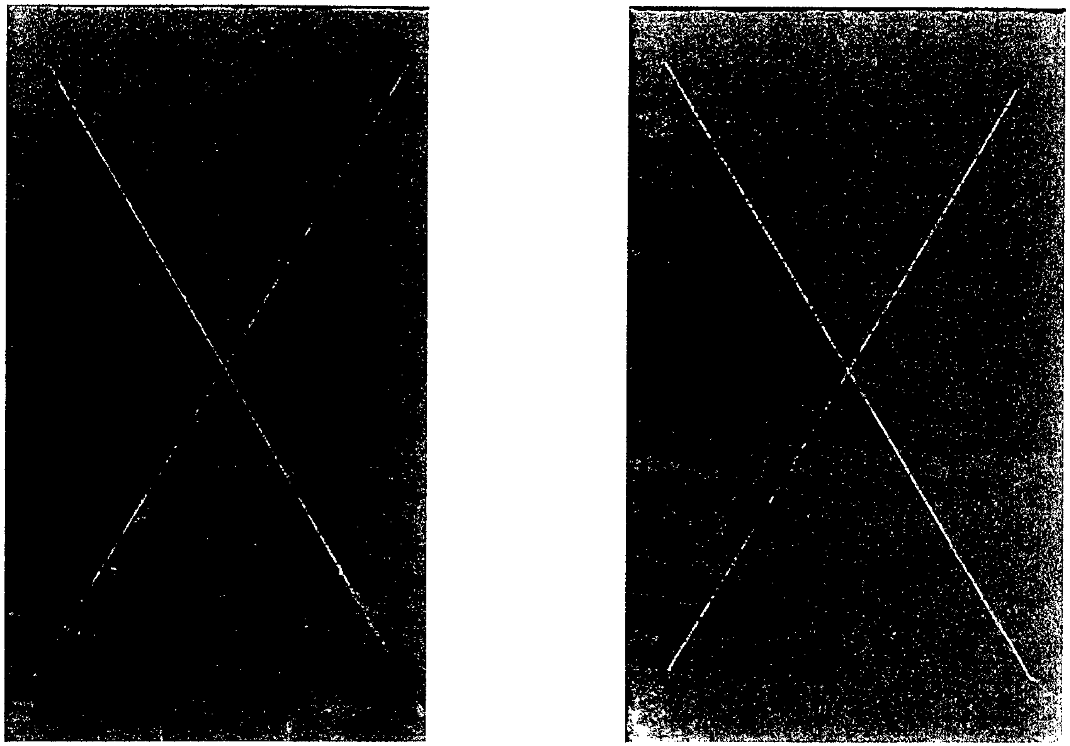
(b) TCP



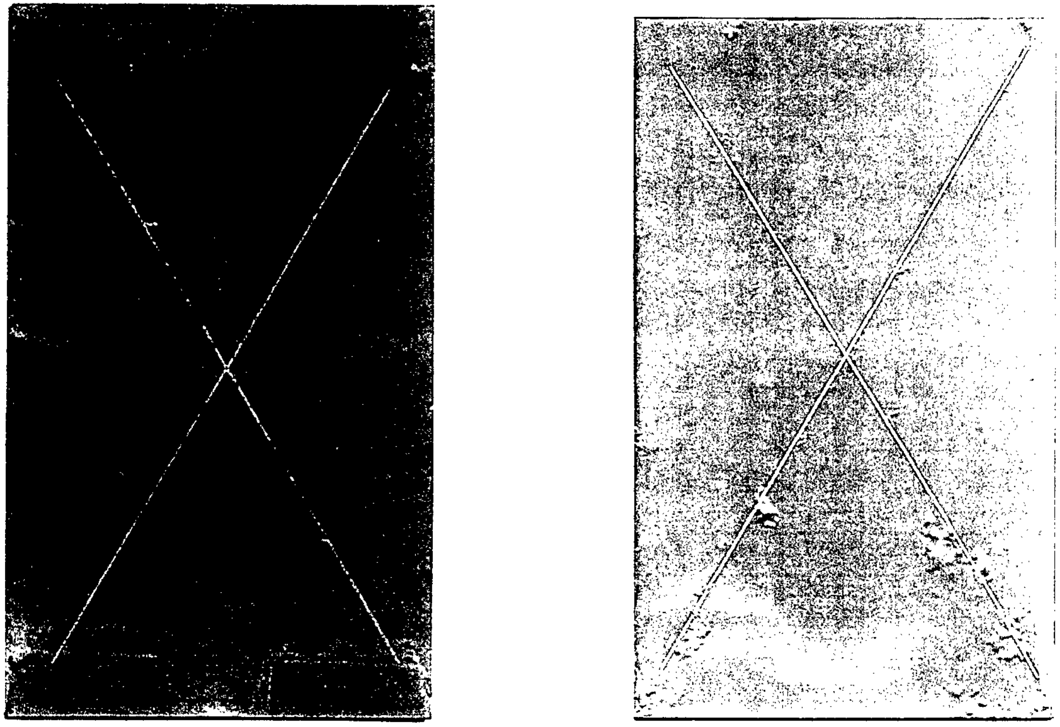
(c) Alodine 5200

(d) Boegel

Figure 9. Al 7075 with 85582nc/85285 at 120 cycles GM 9540P.



(a) Alodine 1200S (b) TCP



(c) Alodine 5200 (d) Boegel

Figure 10. Al 7075 with 53022/53039 at 120 cycles GM 9540P.

such as coating system adhesion, visible color changes to the substrate surface (for quality control) upon pretreatment application, toxicity issues other than Cr^{+6}, as well as the logistics and costs of process application steps, all play significant roles in selection of a viable pretreatment alternative. In order to obtain the most information possible, this overall ESTCP/JG-PP effort includes additional laboratory procedures such as salt fog, SO_2 salt fog, and adhesion methods, all conducted on the same alloy/pretreatment/coating combinations investigated in this portion of the study. Variations in application procedures such as surface preparations, bath conditions for dip processes, and spray applications are also included. These additional results will follow in subsequent ESTCP reports. Information on these documents should become available in time via ESTCP/JG-PP contacts. Ultimately, this compiled database will be offered to help users identify potential alternatives to chromate conversion coatings currently in use by original equipment manufacturers (OEMs) and depots.

It should be noted that it is likely that in various situations more than one pretreatment may be suitable to replace Alodine 1200S. As seen from data in this study as well as in previous studies [11–13], different pretreatments that often work well on one aluminum alloy may not always work well on another. However, this does not necessarily mean that a unique pretreatment is needed for every unique situation. For simplicity, as well as economies of scale, the best possible benefit for replacing Alodine 1200S would be gained by minimizing the number of finalists to as few as possible. A pretreatment that has well-rounded performance across many aluminum alloys would be the most desirable. In this particular study, the best all around non-Cr^{+6} performer was the Cr^{+3} based TCP pretreatment patented by NAVAIR. Toxicity studies on trivalent chromium exposure indicate no carcinogenic or other hazards similar to those found in Cr^{+6} pretreatments such as Alodine 1200S [14, 15]. Nevertheless, environmental regulatory bodies such as those found in California and the European Union have implemented or indicated future stricter guidelines concerning the use of chromium-containing pretreatments.

If trivalent chromium-based pretreatments such as TCP are not acceptable or are denied for implementation due to their total chromium content, the next best performing pretreatments were Alodine 5200 and Boegel. For the most part, performance between these two pretreatments for each alloy was roughly comparable when performance across all variations of coating systems was examined. There are two factors that may favor Alodine 5200 over Boegel. The first is its performance on the Cr^{+6} free organic coating systems 85582nc/85285, 53030/53039, and 53022/53039. For the more corrosion-prone Al alloys 2024 and 7075, Alodine 5200 either met or exceeded Boegel in GM 9540P creepback performance when these chromium free coating systems were used. Previous laboratory and automotive proving ground [16] studies involving Alodine 5200 have also shown good performance on a variety of Al alloys using 53022/53039 based CARC coating systems [11–13]. Second is that Boegel is currently limited to spray and wipe application methods due to mixing and solution shelf life once mixed (1 day maximum).

Currently many prospective Cr^{+6} free pretreatments may simply just be able to "get by" when coated over by Cr^{+6} enhanced organic coating systems. In order to truly determine the enhanced corrosion resistance gained from a hexavalent chromium-free pretreatment, a hexavalent chromium free organic coating system must be used when performing corrosion test methods. Current and future acquisition systems such as the Armored Amphibious Assault Vehicle (AAAV) and the Interim Armored Vehicle (IAV) are already mandating Cr^{+6} free organic coating systems. This trend is likely to continue and potentially may even be applied to some fielded DOD vehicles and weapon systems. In order to clearly delineate the best possible Cr^{+6} free pretreatment(s), additional experimental results in addition to field tests on actual systems from NAVAIR and other participating DOD activities will be critical.

5. Conclusions

- Pretreatment performance varied with varying alloys,
- DOD coating systems formulated with Cr^{+6} additives provided significantly enhanced corrosion resistance versus coatings without Cr^{+6},
- Alodine 5200 and NAVAIR TCP Cr^{+3} performed best overall in GM 9540P cyclic accelerated corrosion among non-Cr^{+6} based pretreatments with performance at or near Cr^{+6} based Alodine 1200S across all alloys and coating systems examined, and
- Commercially available Alodine 5200, in conjunction with the chromium-free organic coatings tested in this study, provides a completely chromium-free coating system with good corrosion resistance.

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Appendix. Complete 120-Cycle GM 9540P Cyclic Corrosion ASTM D 1654 Creepback Ratings

Table A-1. Al 2024–T3 panel designation, coating system, and ratings.

Pretreatment	23377/85285					85582c1/85285					85582nc/85285				
Alodine 1200S	2-51	2-52	2-53	2-54	2-55	2-56	2-57	2-58	2-59	2-60	2-66	2-62	2-63	2-64	2-65
Rating	■	■	■	■	■	■	■	■	■	■	6	6	7	7	6
TCP10 (NAVAIR)	2-151	2-152	2-153	2-154	2-155	2-156	2-157	2-158	2-159	2-660	2-666	2-662	2-663	2-664	2-665
Rating	■	■	■	■	■	7	■	■	■	■	▒ 5	▒ 5	▒ 5	6	6
Alodine 5200	2-251	2-252	2-253	2-254	2-255	2-256	2-257	2-258	2-259	2-260	2-266	2-262	2-263	2-264	2-265
Rating	■	■	■	■	■	▨ 6	■	■	■	■	7	6	6	6	▒ 5
Sanchem 7000	2-351	2-352	2-353	2-354	2-355	2-356	2-357	2-358	2-359	2-360	2-366	2-362	2-363	2-364	2-365
Rating	■	▨ 6	▒ 5	7	■	■	■	■	■	■	■	■	■	■	■
X-IT PreKote	2-451	2-452	2-453	2-454	2-455	2-456	2-457	2-458	2-459	2-460	2-466	2-462	2-463	2-464	2-465
Rating	7	7	7	7	7	▨ 5	▒ 5	7	7	7	▒ 5	▒ 4	▒ 4	▒ 6	▒ 5
Oxsilan AL-0500	2-551	2-552	2-553	2-554	2-555	2-556	2-557	2-558	2-559	2-560	2-566	2-562	2-563	2-564	2-565
Rating	■	■	■	■	■	▨ [illegible]	7	▨ 4	▨ 4	▨ 4	6	6	6	▒ 5	▒ 5
Chemidize 727ND	2-651	2-652	2-653	2-654	2-655	2-656	2-657	2-658	2-659	2-660	2-666	2-662	2-663	2-664	2-665
Rating	■	7	7	■	7	▨ 5	6	7	6	6	▨ [illegible]	▨ [illegible]	▨ 2	▨ [illegible]	▨ [illegible]
BI-K Aklimate	2-751	2-752	2-753	2-754	2-755	2-756	2-757	2-758	2-759	2-760	2-766	2-762	2-763	2-764	2-765
Rating	7	7	■	■	■	▨ [illegible]	▩ [illegible]	7	▨ [illegible]	7	▨ [illegible]	■	■	■	■
Boegel	2-851A	2-852A	2-853A	2-854A	2-855A	2-856A	2-857A	2-858A	2-859A	2-860A	2-866A	2-862A	2-863A	2-864A	2-865A
Rating	■	■	■	■	6	■	■	■	■	7	■	▒ 1	■	▒ 4	■

Note: Solid colors depict normal scribe creepback from corrosion.
Diagonal crosshatching denotes blistering away from immediate scribe regions.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table A-2. Al 2024–T3 panel designation, coating system, and ratings.

Pretreatment	53030/53039					53022/53039				
Alodine 1200S	2-66	2-67	2-68	2-69	7-70	7-71	7-77	7-73	7-74	7-75
Rating	7	6	6	7	6	6	5	6	6	6
TCP10 (NAVAIR)	2-666	2-667	2-668	2-669	7-170	7-171	7-177	7-173	7-174	7-175
Rating	■	■	■	■	6	■	6	7	■	■
Alodine 5200	2-266	2-267	2-268	2-269	7-770	7-771	7-777	7-773	7-774	7-775
Rating	6	■	7	7	5	6	6	7	7	6
Sanchem 7000	2-366	2-367	2-368	2-369	7-370	7-371	7-377	7-373	7-374	7-375
Rating	■	▒ [illegible]	▒ [illegible]	▒ [illegible]	▒ [illegible]	■	■	■	■	■
X-IT PreKote	2-466	2-467	2-468	2-469	7-470	7-471	7-477	7-473	7-474	7-475
Rating	▒ [illegible]	▒ [illegible]	▒ [illegible]	▒ [illegible]	▒ [illegible]	■	■	■	■	■
Oxsilan AL-0500	2-566	2-567	2-568	2-569	7-570	7-571	7-577	7-573	7-574	7-575
Rating	▒ [illegible]	■	■	▒ [illegible]	■	▒ [illegible]	▒ [illegible]	6	■	▒ [illegible]
Chemidize 727ND	2-666	2-667	2-668	2-669	7-670	7-671	7-677	7-673	7-674	7-675
Rating	■	■	■	■	■	■	■	■	▒ [illegible]	■
BI-K Aklimate	2-766	2-767	2-768	2-769	7-770	7-771	7-777	7-773	7-774	7-775
Rating	▒ 5	■	■	■	■	7	▨ [illegible]	▨ [illegible]	▨ [illegible]	▨ [illegible]
Boegel	2-866A	2-867A	2-868A	2-869A	7-870A	7-871A	7-877A	7-873A	7-874A	7-875A
Rating	▒ [illegible]	■	■	■	■	6	■	■	■	■

Note: Solid colors depict normal scribe creepback from corrosion.

Table A-3. Al 2219–T87 panel designation, coating system, and ratings.

Pretreatment	23377/85285					85582c1/85285					85582nc/85285				
Alodine 1200S	9-51	9-52	9-53	9-54	9-55	9-56	9-57	9-58	9-59	9-60	9-66	9-62	9-63	9-64	9-65
Rating					6						7	7	6		6
TCP10 (NAVAIR)	9-151	9-152	9-153	9-154	9-155	9-156	9-157	9-158	9-159	9-660	9-666	9-662	9-663	9-664	9-665
Rating	7		7						7			6			
Alodine 5200	9-251	9-252	9-253	9-254	9-255	9-256	9-257	9-258	9-259	9-260	9-266	9-262	9-263	9-264	9-265
Rating													7	7	6
Sanchem 7000	9-351	9-352	9-353	9-354	9-355	9-356	9-357	9-358	9-359	9-360	9-366	9-362	9-363	9-364	9-365
Rating	6	7			7	6	7	6							
X-IT PreKote	9-451	9-452	9-453	9-454	9-455	9-456	9-457	9-458	9-459	9-460	9-466	9-462	9-463	9-464	9-465
Rating						7	7	6	6	7					
Oxsilan AL-0500	9-551	9-552	9-553	9-554	9-555	9-556	9-557	9-558	9-559	9-560	9-566	9-562	9-563	9-564	9-565
Rating															
Chemidize 727ND	9-651	9-652	9-653	9-654	9-655	9-656	9-657	9-658	9-659	9-660	9-666	9-662	9-663	9-664	9-665
Rating							7	7							
BI-K Aklimate	9-751	9-752	9-753	9-754	9-755	9-756	9-757	9-758	9-759	9-760	9-766	9-762	9-763	9-764	9-765
Rating	5			7	7	7	6	5							
Boegel	9-851A	9-852A	9-853A	9-854A	9-855A	9-856A	9-857A	9-858A	9-859A	9-860A	9-866A	9-862A	9-863A	9-864A	9-865A
Rating	6						7	6		7					

Note: Solid colors depict normal scribe creepback from corrosion.

Table A-4. Al 2219–T87 panel designation, coating system, and ratings.

Pretreatment	53030/53039					53022/53039				
Alodine 1200S	9-66	9-67	9-68	9-69	9-70	9-71	9-77	9-73	9-74	9-75
Rating										
TCP10 (NAVAIR)	9-666	9-667	9-668	9-669	9-170	9-171	9-177	9-173	9-174	9-175
Rating										
Alodine 5200	9-266	9-267	9-268	9-269	9-770	9-771	9-777	9-773	9-774	9-775
Rating										
Sanchem 7000	9-366	9-367	9-368	9-369	9-370	9-371	9-377	9-373	9-374	9-375
Rating										
X-IT PreKote	9-466	9-467	9-468	9-469	9-470	9-471	9-477	9-473	9-474	9-475
Rating										
Oxsilan AL-0500	9-566	9-567	9-568	9-569	9-570	9-571	9-577	9-573	9-574	9-575
Rating										
Chemidize 727ND	9-666	9-667	9-668	9-669	9-670	9-671	9-677	9-673	9-674	9-675
Rating										
BI-K Aklimate	9-766	9-767	9-768	9-769	9-770	9-771	9-777	9-773	9-774	9-775
Rating										
Boegel	9-866A	9-867A	9-868A	9-869A	9-870A	9-871A	9-877A	9-873A	9-874A	9-875A
Rating										

Note: Solid colors depict normal scribe creepback from corrosion.

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14. ABSTRACT
This study examines corrosion resistance of eight nonchromate conversion coatings versus hexavalent chromium based Alodine 1200 controls on scribed coated test panels of aluminum alloys 2024, 2219, 5083, and 7075. Five representative DOD primer/topcoat organic coating systems were evaluated for each of the conversion coating/alloy combinations. Scribed panels were exposed using GM 9540P for 120 cycles duration and were photographed and measured at 20 cycle intermediate intervals for scribe creepback using method ASTM D 1654. Differences in pretreatment performance based upon variation in coating type as well as alloy were noted. How these data may relate with respect to implementation of nonchromate pretreatments for different military applications is discussed.

15. SUBJECT TERMS
corrosion, cyclic accelerated corrosion, GM9540P, aluminum, nonchromate, hexavalent, chromate, conversion coating

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